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JANUARY 1963

DETERMINING ECONOMIC QUANTITIES OF MAINTENANCE RESOURCES: A MINUTEMAN APPLICATION

Chauncey F. Bell and Milton Kamins

PREPARED FOR:
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SANTA MONICA • CALIFORNIA

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PREFACE

This Memorandum is part of a long-term study of maintenance policies and their effect on Air Force capabilities and costs. It presents a method for determining economically desirable levels of maintenance support -- equipment and personnel -- with specific application to the Minuteman weapon system.

A series of RAND briefings on logistics aspects of the Minuteman program* (the result of a study requested by the Deputy Chief of Staff, Materiel) led to an invitation from the Ballistic Systems Division, AFSC, to attend Minuteman maintenance-loading conferences held late in 1961 and early 1962 for the purpose of procuring maintenance ground equipment and quantifying personnel requirements. At these conferences the inadequacies of both earlier RAND work and current Air Force methodology became apparent. Encouraged by BSD, SAC, and Ogden AMA personnel involved in the program, the authors developed a new technique that takes into account several critical but frequently overlooked factors and participated in its trial for determining Minuteman maintenance ground equipment (MGE) quantities in the spring of 1962. Publication of the technique was delayed, however, until the results of its use could be compared with the results of sophisticated computer simulations of the maintenance processes of the Minuteman system.

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*Chauncey F. Bell, Jr., An Evaluation of Logistics Aspects for the Minuteman Program (U), The RAND Corporation, B-259, May 24, 1961 (Secret).

Although the technique is tailored to the Minuteman ICBM, the approach and method can be directly applied to other new systems; consequently, this Memorandum should be of interest to those Air Force organizations concerned with early support planning and programming.

SUMMARY

Several years ago, when new weapon systems usually had some marked similarity to existing weapons, manpower and equipment requirements were established largely on the basis of the demonstrated needs of an old system. With the advent of the first ICBM, however, this method proved unsatisfactory because there was no obvious comparison to be made with the past. As a consequence, specifications were written which called for identification of the types of manpower and ground equipment required for a new system. The formulas developed to establish quantitative maintenance manpower and equipment requirements, however, implicitly assume that there is either a backlog of work requiring these resources, or that the work will arrive at a uniform rate. These assumptions are unrealistic and will result in inadequate logistic support and probably unacceptable degradation in operational capability. This has been recognized as recently as the July 1962 Minuteman Qualitative Personnel Requirements Information document, which stated in part that manpower loading figures were applicable to ideal conditions only and should be augmented to compensate for limitations imposed by operational conditions. In efforts to compensate for these deficiencies, the formula requirements have been adjusted in many cases, but without any real confidence that the adjustments were appropriate.

This Memorandum introduces a technique for computing manpower and equipment requirements that takes into account three critical and frequently overlooked factors. These are: the randomness of the failure pattern -- the uncertainty of the time any particular

malfunction will occur; the workshift policy -- when maintenance personnel are on duty; and the cost-effectiveness tradeoff -- the marginal increase in system capability weighed against the cost of providing a marginal increase in resources. The quantities of maintenance personnel and ground equipment estimated with the technique presented here will economically meet anticipated requirements within the accuracy limitations of the three inputs necessary to the computation. These are: failure rate or reliability, repair time or maintainability, and cost.

To illustrate the technique, a set of curves specifically tailored to the Minuteman ICBM are provided. To use these curves, one must first compute the team-hours or equipment-hours per month spent in-transit and on-the-job, and enter this information on the curves. The needed quantities are then read out, based on the cost of the resource, the allowable force degradation for this one resource type, or both. In this manner, one can determine not only the desired quantity from a cost-effectiveness point of view, but also the penalty involved if this quantity is not chosen. In addition, it is possible to examine the effects of failure to meet reliability, maintainability, or equipment cost estimates from both the point of view of consequent changes in requirements and of force readiness degradation.

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I. INTRODUCTION

BACKGROUND

It has always been necessary to establish specific requirements for maintenance personnel and maintenance ground equipment before any substantial amount of relevant data was available. Long lead-times for training personnel in the detailed knowledge necessary for effective maintenance, and long leadtimes required for procurement of expensive equipment items have contributed to this situation. In recent years the concurrency concept and the increasing complexity of new weapon systems have aggravated the situation to the point where improved prediction techniques are more desirable than ever before.

A number of years ago, when each new weapon system had some marked similarity to current weapons, manpower and equipment requirements were established largely on the basis of demonstrated needs of an old system. This occasionally led to such errors as the inclusion of propeller mechanics for early jet aircraft, but by-and-large was considered satisfactory. With the advent of the first Inter-Continental Ballistic Missile, however, the Air Force found itself in considerable difficulty because there was no obvious comparison to be made with the past. Specifications were written establishing need for certain estimated data[1][2] and a Qualitative Personnel Requirements Information (QPRI) document was developed.[3] These called for task analyses, identification of each possible scheduled or unscheduled maintenance task which might be generated under the operational concept, so that skill types and skill levels could be

specified in the manning documents. For lack of a better way to quantify, apparently, the tasks for a given type of specialist were summed. Thus if a particular specialist type was necessary for three kinds of tasks, three were called for. If only one task had been identified, one specialist was requested. This approach insured at least one of each specialist type, but understated requirements when job times were long. What was really needed, of course, was a quantitative, as well as a qualitative (QQPRI) approach. More recently, the Air Force developed a specification to provide information necessary for equipment procurement.[4]

NEED

In 1957 RAND published a study directly concerned with the ATLAS ICBM[5] which indicated that substantial degradation in operational capability would result from inadequate support resources, including maintenance personnel and equipment. Similar manned aircraft studies published between 1957-1959 were highlighting the same point;[6-9] and a missile logistics "game" was devised to dramatize this effect.[10] Recent RAND studies concerned with the Minuteman ICBM have again indicated the unacceptable degradation in operational capability resulting from inadequate logistic support, as well as the high cost of providing unnecessary support.[11][12]

During 1958-1959 we suggested some ways of approaching the quantification problem for maintenance personnel[13][14] and carried

some of these ideas out in a simulation experiment concerned with first-generation ICBM's.*(15)(16)

CURRENT SITUATION

The Minuteman ICBM program has incorporated substantial improvements over early ATLAS data in the type, quality and presentation of personnel requirements information. For the first time, essentially all of the types of information necessary for accurate computation of manpower and equipment requirements are provided. Of necessity, the information usually represents best estimates or design goals at this time. It is important to note in passing that significant difficulties remain to be overcome before operational data can be used to update initial estimates.

Formulas have been developed to compute the quantities of maintenance personnel (thus a QQPRI) or maintenance ground equipment needed on the basis of estimated utilization established by the aforementioned information. These formulas implicitly assume either that there is a backlog of work requiring these resources, or that the work will arrive in a uniform manner. It is recognized that these assumptions are unrealistic and understate the true requirements. In many cases, adjustments in formula requirements are made to compensate for the shortcomings.

*Other RAND work, useful at a much earlier point in the weapon development cycle, includes M. C. Heuston, Concepts for Estimating Air Force Manpower Requirements for Planning Purposes, The RAND Corporation, RM-2611 (AD 250725), December 1, 1960.

The Minuteman QPRI document of July 1962[17] states in part:

> The manpower loading figures are, applicable to ideal conditions only and should be augmented to compensate for limitations imposed by operational conditions. If the Air Force has sufficient confidence that the augmentation factor can be developed based upon past experience and sound management programming, the current estimating formula can be considered as sufficient in providing base line manpower loading.
>
> If the Air Force is not able to generate an augmentation factor in which they have sufficient confidence, additional work should be done with mathematical models and/or computer simulations to develop a more accurate formula that would take fuller cognizance of operational considerations such as the maintenance philosophy and shift and dispatch policy. This approach would be especially helpful in supporting advanced models of the WS-133A or future Weapon Systems.

OUTLINE OF STUDY

This Memorandum introduces a technique for computing quantitative maintenance manpower and maintenance ground equipment requirements, taking into account four of the most critical factors: frequency of demand for the resource; maintenance time necessary for servicing the resource; randomness of the demand pattern -- the uncertainty about the time of any particular malfunction; and the cost-effectiveness factors -- the value of the marginal increase in system capability weighed against the marginal cost of resources required to achieve that capability. Using published utilization estimates and the pertinent cost information, sets of charts developed here for the purpose are used to arrive at appropriate manpower and ground equipment quantities. This study makes no effort to alter current qualitative requirements methodology.

Section II describes the rationale and methodology used in developing the charts (an example of curve construction appears in the Appendix), so that the approach can be used for weapon systems other than the Minuteman. Section III presents the charts and explains their use. Section IV examines the principal simplifications and assumptions inherent in the method of this Memorandum, and the probable effect of these assumptions on the numerical answers developed by the method. Conclusions appear in Section V.

II. DETERMINING RESOURCE REQUIREMENTS

DATA NEEDS

The basic information requirements for determining the quantity of maintenance personnel or maintenance ground equipment needed to support a particular operation are estimates or factual data concerning the frequency of demands for the particular resource and the average length of time the resource will be occupied in fulfilling the demands. If economics enters the evaluation* then the costs of providing resource increments and the value of the resulting incremental operational capability must also be known. The Minuteman weapon system specifications provide such workload factors.(17-20) Failure rates for systems and subsystems are estimated, in terms of failures per month for a 150 missile wing. "Time lines" indicate how long each type of resource will be tied up in performing each task, including travel times to site, etc. The product of these two pieces of information, for a given equipment item or a particular maintenance team, will yield the monthly utilization in hours.

If one is concerned only with resource utilization, the necessary quantity can be determined easily and directly. Suppose, for instance, that a particular major component has an estimated failure rate of 50 per month for a 150 missile wing, and that each failure can be expected to tie up a certain piece of equipment and associated team for 50 hours. Utilization is 2500 hours per month. Assume 250

---

*And we believe that it should, in that the goal is to maximize the operational capability per dollar spent, rather than to support a particular capability regardless of cost.

hours per month permissible utilization of the equipment (perhaps 8 hours per day, 31 days a month), and it is seen that 10 sets of in-commission equipment are required with this method of calculation. Assume 140 hours per month per team, to allow for leave, illness, squadron duties, etc., and 18 teams of maintenance personnel need to be assigned. Utilization of teams and equipment alike would be nearly 100 per cent, a very "efficient" operation. A substantial part of the force would be kept waiting its turn in line, however, unless each new failure occurred just as the previous one had been corrected -- and we know that this does not happen. There are those days when all goes well, and those when everything goes wrong.

RATIONALE

Large bodies of data indicate that complex weapon systems usually experience malfunctions distributed in a "random" fashion. For example, let us assume data has shown or engineering estimates indicated that 3 per cent of the 150 missile wing will malfunction on an average day; thus there will be an expected 135 failures per 30-day month. For the moment also assume there is one standard piece of equipment and maintenance team which handles these failures, and that each failure takes exactly 2 days to repair. Using a

table of random numbers [21] and applying the 3-per-cent failure probability, the following failures occurred for a 30-day month.*

Day	No. of Failures	Day	No. of Failures
1	8	16	2
2	11	17	4
3	4	18	1
4	6	19	4
5	5	20	3
6	3	21	0
7	3	22	3
8	4	23	5
9	1	24	7
10	3	25	4
11	0	26	4
12	1	27	5
13	4	28	3
14	3	29	4
15	1	30	4

This month has only 110 failures, instead of the expected 135. In some months there will be substantially more failures than the

*With a 3-per-cent failure probability for each of 150 missiles, the expected number of failures per day is simply 3 per cent of 150 or 4.5. With this rate, the probability of having a particular number of failures on any given day is, from a table of Poisson's Exponential Binomial Limit:[22]

No.	Probability	No.	Probability	No.	Probability
0	0.011	5	0.171	10	0.010
1	0.050	6	0.128	11	0.004
2	0.112	7	0.082	12	0.002
3	0.169	8	0.046	13	0.001
4	0.190	9	0.023	14	0.000

We now draw three-digit random numbers. If the number drawn is from 1 to 11, there are no failures that day; if from 12 to 61, one failure; if from 62 to 173, two failures, etc.

average expected. Figure 1 shows this month's distribution. There were 2 days with no failure, 9 days with 4 failures, 1 day with 11, etc. The "expected" distribution is also shown. Despite the lower-than-usual monthly workload, we can expect some workload control problems, especially since the two heaviest days fall one after the other, on the 1st and 2nd of the month. Figure 2 indicates the workload for the month, assuming that each job is discovered and started at the beginning of one day, and is completed at the end of the second day. A carryover of 4 jobs from last month (assumed, based on last day this month) plus 8 more on day 1, occupies 12 teams; the carryover of 8, plus 11 on day 2, results in the peak load of 19 teams. No new work on day 11 and only 1 job on day 12, results in almost no work by contrast.

To perform this month's work without any delays, then, will require 19 teams on duty, although team utilization would only be about 39 per cent. Suppose we had only 18 teams, the unit of work numbered (1) would have to be delayed from day 2 to day 3. With only 14 teams, units of work numbered (1) through (6) would have to be delayed for the periods indicated. There would be a total of 13 alert missile days lost. Table 1 indicates the story as teams are cut progressively to 9, where 172 alert missile days are lost waiting for teams (nearly 6 missiles on the average each day), and yet team utilization is only 82 per cent.

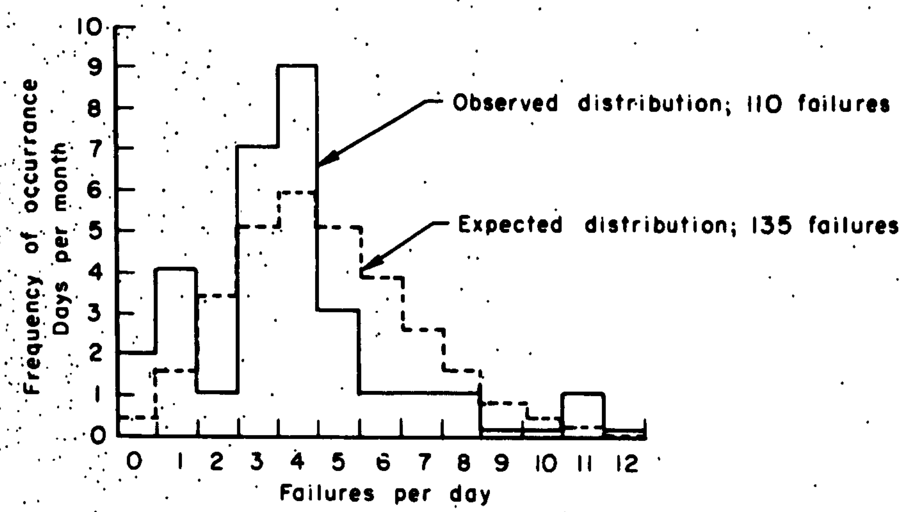

Fig. 1 — Distribution of failures for a random month

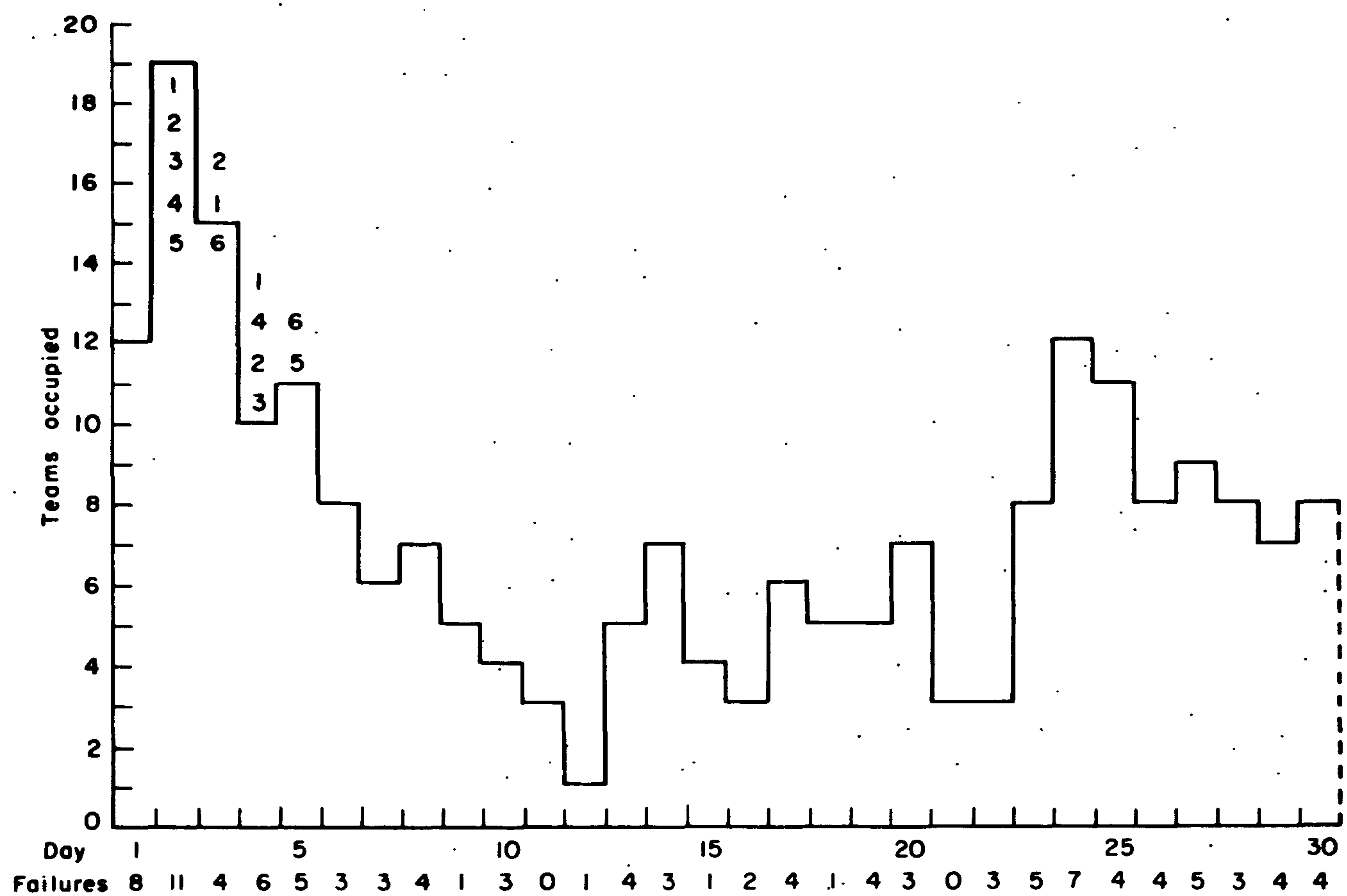

Fig. 2 — Workload distribution for a random month

Table 1

MISSILE WORK DELAYS AS A FUNCTION OF NUMBER OF TEAMS FOR A RANDOM MONTH

No. of Teams	Percent Utili-zation	Alert Missile-Days Lost Wait-ing for Teams
19	39	0
18	41	1
17	43	2
16	46	5
15	49	8
14	52	13
13	57	22
12	61	35
11	67	62
10	73	105
9	82	172

We have already indicated that this month's experience was "unusual," both in having fewer failures than expected and in the failure distribution. We will enter the table of random numbers again, therefore, to establish a second month's experience. Figure 3 shows the distribution, and Fig. 4 the workload. This time there were 131 failures (vs. the 135 expected). Table 2 presents the story as the number of teams are reduced, as did Table 1 for the first month.

Table 2

MISSILE WORK DELAYS AS A FUNCTION OF NUMBER OF TEAMS FOR A RANDOM MONTH

No. of Teams	Percent Utili-zation	Alert Missile-Days Lost Wait-ing for Teams
14	62	0
13	68	1
12	73	7
11	80	18
10	88	42
9	97	132

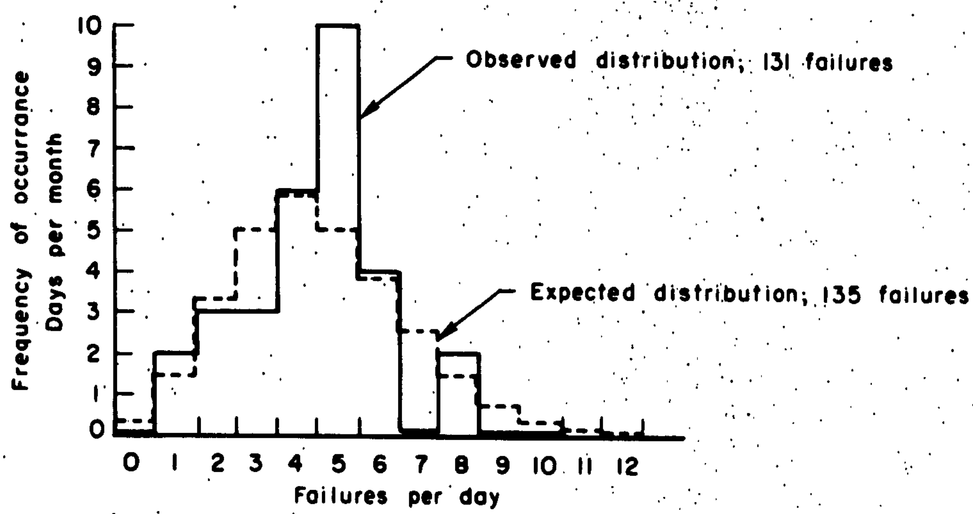

Fig. 3 — Distribution of failures for a second month

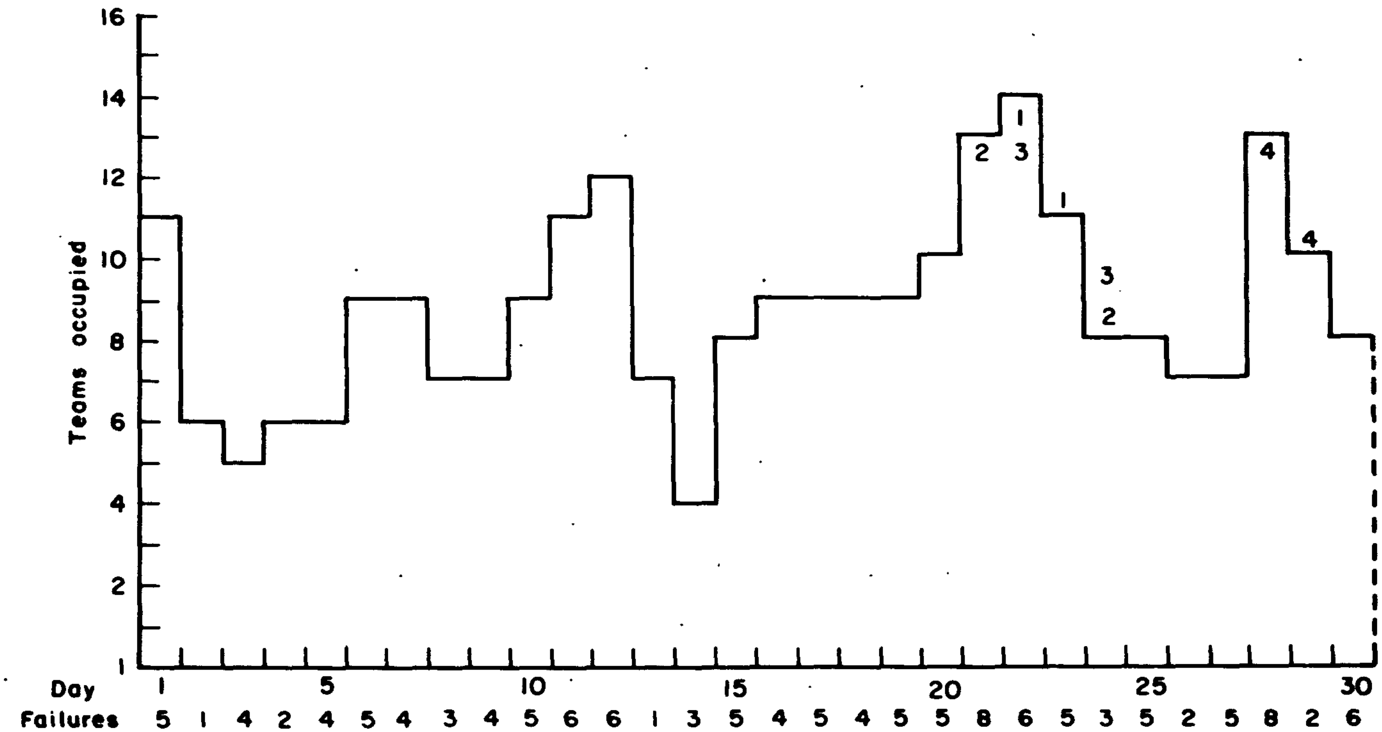

Fig. 4 — Workload distribution for a second month

Again the incompatibility of high utilization of maintenance resources and a high degree of operational readiness is evident. At the extremes of the two tables, we choose between team utilization of only 40 to 60 per cent and maximum possible force readiness, or team utilization of 80 to 95 per cent with an average five or so missiles waiting for maintenance at all times.

At this point we believe that cost considerations should enter the picture. We could provide the wing maintenance organization with an average, in this example, of five or so missile installations of reparable backlog to insure relatively high utilization or "efficiency" of maintenance personnel and equipment resources. Or we could provide the maintenance organization with seven or so additional on-duty teams in order that the operational forces may have about five more ready missiles on the average. Given these two extreme alternatives, we believe it is clear that the cost per ready missile in the force will be less if additional teams are provided; because the teams, plus the necessary maintenance ground equipment (MGE) will cost less than the five missile sites plus missiles.

Some intermediate point may be better than either extreme, however. Assume, for illustration, that the following costs have been estimated for this organization:

1/150 of initial cost of a 150-missile wing .	$3,725,000
Annual operating cost of this fraction	350,000
Annual cost of a team of 4 men	30,000
Initial cost of the MGE* needed by the team	250,000
Annual maintenance cost of the MGE	30,000

*Maintenance Ground Equipment

Further, assume that the force will be in existence for five years, so that initial costs must be depreciated over that period. We then find that the daily cost of a one-missile "slice" of the wing is $3,000, and the daily cost of one team with its MGE is $300. Table 1 information can now be used by computing the monthly savings in team costs as they are reduced from 19, and the monthly losses in down missiles as lack of teams prevent their repair. Table 3 illustrates these computations.

The easiest way to understand the implications of this table is to read from the bottom up. You will recall from Table 1 that 9 teams, busy 82 per cent of the time, can maintain the wing at a cost of 172 missile-days waiting for teams per month. Adding one team will decrease missile waiting time to 105 days per month. The added team costs $300 per day or $9,000 per month. The missile days saved, at $3,000 per day, are worth $201,000 per month. In reverse, the <u>cost</u> of having only 9 teams, instead of 10, is $192,000 per month, or $11,520,000 over the five year period the weapon is in the force. In this hypothetical case, the minimum number of teams to have is 15. However, two additional teams (a total of 17) would be desirable to provide insurance against higher failure rates than anticipated and improve operating flexibility; their net cost to the system is zero on a cost-effectiveness basis. Thus <u>it pays</u> to

Table 3

NET WING SAVING (OR COST) AS A FUNCTION OF NUMBER OF TEAMS FOR A RANDOM MONTH

No. of teams	Missile-days per month waiting for teams	Incremental saving in teams ($/month)	Incremental missile cost	Net saving or (cost)
20	0			
19	0	9,000	0	9,000
18	1	9,000	3,000	6,000
17	2	9,000	3,000	6,000
16	5	9,000	9,000	00
15	8	9,000	9,000	00
14	13	9,000	15,000	(6,000)
13	22	9,000	27,000	(18,000)
12	35	9,000	39,000	(30,000)
11	62	9,000	81,000	(72,000)
10	105	9,000	129,000	(120,000)
9	172	9,000	201,000	(192,000)

have team utilization of 43 to 49 per cent and is very costly ($11,520,000) to have high utilization of 82 per cent.*

METHODOLOGY

In 1958, Peck and Hazelwood produced a set of finite queuing tables in which they stated:**

> This monograph is intended to provide useful tables for the solution of a variety of queuing problems. There are several textbooks and monographs which discuss the theoretical aspects of queuing theory, and the literature contains an impressive number of research papers dealing with such problems. However, there is a paucity of directions for useful applications of these ideas. A person exposed to the concepts of queues is able to recognize broad areas where the theory could be applied, but he is often at a loss to find ways of solving the problems.
> .....
> In general, queuing theory deals with the formation of a queue, or waiting line. Suppose there is some service point, such as ... a repairman servicing a broken machine, etc. Part of the time this service point will be busy providing service, part of the time it will be idle. If the service point or "channel" is busy and another customer arrives, he must wait. This forms a queue.

This situation fits our missile force where missiles or aerospace ground equipment and facilities, requiring maintenance, are the "customers," and maintenance teams are the service points.

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*It should be emphasized that this cost-tradeoff procedure is conservative. From a strict economic standpoint, the cost per missile-day should be divided by the operational ready rate, thus increasing the cost of down missiles. Further, enemy damage to us because one of our missiles did not operate will be many times higher than out-of-pocket cost, used here.

**See p. vii of Ref. 23.

Using our hypothetical example presented earlier, let us enter the Peck and Hazelwood tables and examine the findings. A typical portion looks like the following:

POPULATION, N = 150

X	M	D	F
.025	7	.096	.999
	6	.215	.998
	5	.438	.992
	4	.785	.966
.026	7	.113	.999
	6	.247	.997
	5	.487	.990
	4	.838	.955
.028	7	.154	.999

The population represents the number of "customers" which can demand service -- in the Minuteman case 150 missiles. X = service factor = $\frac{T}{T + U}$ where T = average service time or repair time, and U = average time not calling for service -- in our case the mean time between failures. M = service channels or number of repair teams. D = probability that if a unit calls for service it will have to wait ("delay" probability). F = efficiency factor = $\frac{H + J}{H + J + L}$ where H = average number of units being serviced, J = average number of units running (on alert), and L = average number of units waiting for service.

Assumptions in the hypothetical case were that 3 per cent of the wing would malfunction each day, on the average, and take 2 days to repair. Thus T = 2, U = 33.3 days, and $X = \frac{2}{2 + 33.3} = .057$. The tables have X = .056 and X = .058. Rather than interpolate, the section for population 150, X = .058, is reproduced below.

X	M	D	F
.058	14	.060	.999
	12	.198	.997
	11	.330	.993
	10	.518	.985
	9	.747	.962
	8	.939	.905

L, the average number of units waiting for service, can be represented as L = N(1-F). Thus with 9 teams, for instance, L = 150 (1-.962) = 5.7 missiles. This is 5.7 x 30 = 171 missile days per month.

Table 4 compares the queued missiles vs. teams for the random month of Tables 1 and 2 respectively, and per Peck and Hazelwood.

Table 4

MISSILE WORK DELAYS VS. NUMBER OF TEAMS
Peck and Hazelwood; Tables 1 & 2

No. of Teams	Missile Days Queued		
	Table 1	Table 2	P & H
14	13	0	4.5
12	35	7	13.5
11	62	18	31.5
10	105	42	67.5
9	172	132	171.0

Notice that P & H values are compatible with those of the two random months. We re-emphasize here that one random month is wholly inadequate to properly determine the distribution of demands, these examples being given only to illustrate the principles. Peck and Hazelwood tables embrace certain assumptions which are discussed in a following section.

We hope that two major points are clearer now: (1) high utilization of resources in the correction of critical malfunctions

(those preventing launch of the missile) is incompatible with high mission readiness, and therefore uneconomical; (2) it should be possible to develop a technique that can use cost-effectiveness criteria to measure the interaction between number of teams available and number of missiles or related equipment.

We have used the Finite Queuing Tables in a straightforward way to develop sets of curves so that proper quantities of resources may be determined. The following Section presents the curves and explains their use. A succeeding Section explains in detail the assumptions embodied in the curves. Appendix A explains their derivation, and Appendix B presents an alternate method embodying the same principles in a simpler, but less flexible procedure.

III. DETERMINING MINUTEMAN MANPOWER AND EQUIPMENT QUANTITIES

This Section presents curves developed specifically for the Minuteman weapon system which is organized in wings of 150 missiles. Determining quantities of sets of maintenance ground equipment is discussed first, because there are somewhat fewer ramifications than in determining manpower requirements. Figure 5, Equipment Requirements vs. Monthly Utilization, presents a series of curves fanning out from the origin.* The figure is used as follows. Suppose it has been determined that a particular type of maintenance van will be used for 1750 hours per month in unscheduled maintenance (the correction of malfunctions which result in a non-ready missile or missiles).** Read 1750 on the abscissa and move up vertically to the top line, then move to the left and read 5 sets of equipment (21 shifts per week). This means that if maintenance policy permits responding to a call during any of the 3 possible 8-hour shifts, 7 days a week (3 x 7 = 21 shifts), then providing 5 vans (assuming 100 per cent in-commission) will result in a minimum number of down missiles awaiting vans to return from some other job. Specifically, the top line calls for an average of 0.075 missiles waiting for this reason in a 150-missile wing (something which will happen, according to the Peck and Hazelwood tables, less than 5 per cent of the time).

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*Construction of the curves is demonstrated by an example in the Appendix.

**For instance, we estimate 14 malfunctions per month and 125 hours clock time to travel to the site, correct each malfunction, return to the base, and get ready for the next call.

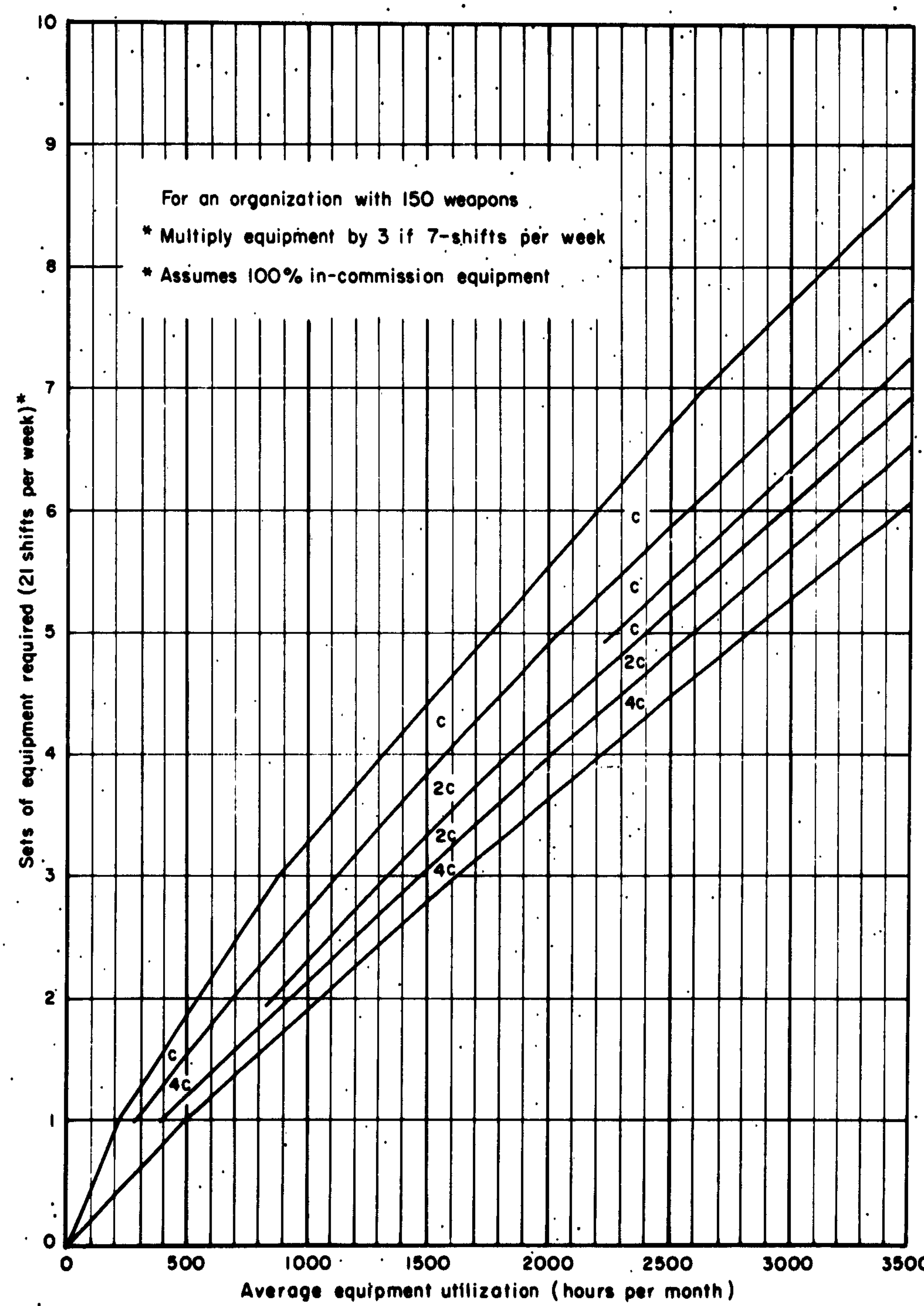

Fig. 5 — Equipment requirements versus monthly utilization

The next step in using the curves is to see if providng only 4 (in-commission) vans would be economically satisfactory. Move horizontally from the 4 to the intersection with 1750 hours, and we find a point slightly below the second curve. Notice that the space between each curve is labelled "C," or "2C," etc. We have moved down about 2.2C from the top line. Each "C" represents .001 of the force, or wing in this case, or 0.15 missile. This means that an additional 0.33 missiles will be kept waiting, on the average, for lack of the 5th van. In terms of our previous examples, this is 9.9 missile days per month (in addition to the 2.25 missile days per month when five vans are available). If a missile day is worth $3,000.00, then the 5th van is desirable provided its monthly cost (including teams to accompany it) does not exceed $3,000.00 x 9.9 = $29,700.00 (most equipment costs will be much less than this.)*

Suppose that maintenance policy is such that work is performed only 12 hours per day, 7 days per week. From the standpoint of logic, about twice as many vans will be needed because they are now "forced" to be idle half of the time. Actually this is a slight oversimplification. The recommended procedure is to recompute the hours per month during which the vans will be tied up in unscheduled maintenance, taking into account the off-shift time. Ih our hypothetical example, we now multiply 14 malfunctions by 250 hours (125 x 2, which compensates for the half-time usage) to establish "workload" of 3500 hours, and find that 9 vans (or possibly only 8) will be needed instead of 5.

*Appendix B contains a one-step procedure for translating projected usage and costs into a recommended quantity, but the tradeoffs are not discernible.

The next item to consider is the number of "spare" vans needed to care for maintenance requirements on the vans themselves (heretofore we have implicitly assumed 100 per cent in-commission rate). The crucial point is whether a van is or is not available to respond to a call. In establishing van requirements, it does not matter whether a van is out caring for the repair of a missile, or is "out" for correction of its own troubles. Therefore we proceed as follows. Going back to our original around-the-clock maintenance policy, we found that 5 vans were required to correct 14 malfunctions, or about 3 trips each per month. For illustration, assume van difficulty 20 per cent of the time. Then there will be 2.8 van malfunctions per month. Assume 15 hours to correct each malfunction, and an additional 42 van hours should be added to the 1750. Examination of the curves indicates that this adds about 0.1 van to the requirement, or conversely adds about 0.1C or less than 0.5 missile days down per month.

One can also examine the effect of increased workload on operational posture via this curve. Suppose that on the basis of an estimated workload of 1750 hours for this van per month, 5 have been procured. However, due to inaccurate estimates, an average of 18 failures per month develops, and each takes an average of 150 hours to correct. Workload time is therefore 2700 hours per month. Move horizontally across the "5 van line" to 2700 hours, and you discover that an additional 7.0C of down time accrues to this van. This represents an average of 1.05 missiles or 31.5 alert missile days lost per month in connection with this type of van. Of course, a

similar computation must be made for each support resource to determine the cumulative effect of the misjudgment in workload.

Manpower requirements are determined in similar fashion from Fig. 6. At first glance it would appear that the charts are identical except that the number of maintenance teams represents 5.2 times the number of equipments, and this is, in fact, so. If we were concerned only with a maintenance policy of continuous coverage, 24 hours a day, 7 days a week, the two curves should be melded into one and maintenance teams computed in this way. But if, however, we are concerned with computing requirements for, say, 12-hour shifts, 7 days a week, then the relationship does not hold. Regardless of shift policy, the number of maintenance teams required remains essentially the same for a given expected utilization in hours per month and desired level of availability (the particular curve chosen); but this does not hold true for equipment. This occurs because we limit personnel to some number of hours' work per month, such as 140, while equipment can be "worked" up to 24 hours per day, day in and day out, barring breakdowns. Actually then, there is more inherent flexibility in manpower than there is in equipment, given round-the-clock operation, since people can work more than their planned 140 hours per month. Of course, if equipment is scheduled for only 12 hours per day, it can be stretched by increasing the length or number of shifts.

The cost of manpower must be combined with cost of the equipment, and the exact quantity of equipment determined before establishing manpower quantities. Manpower should be chosen to be compatible with the equipment, that is, at the same point <u>vis-à-vis</u>

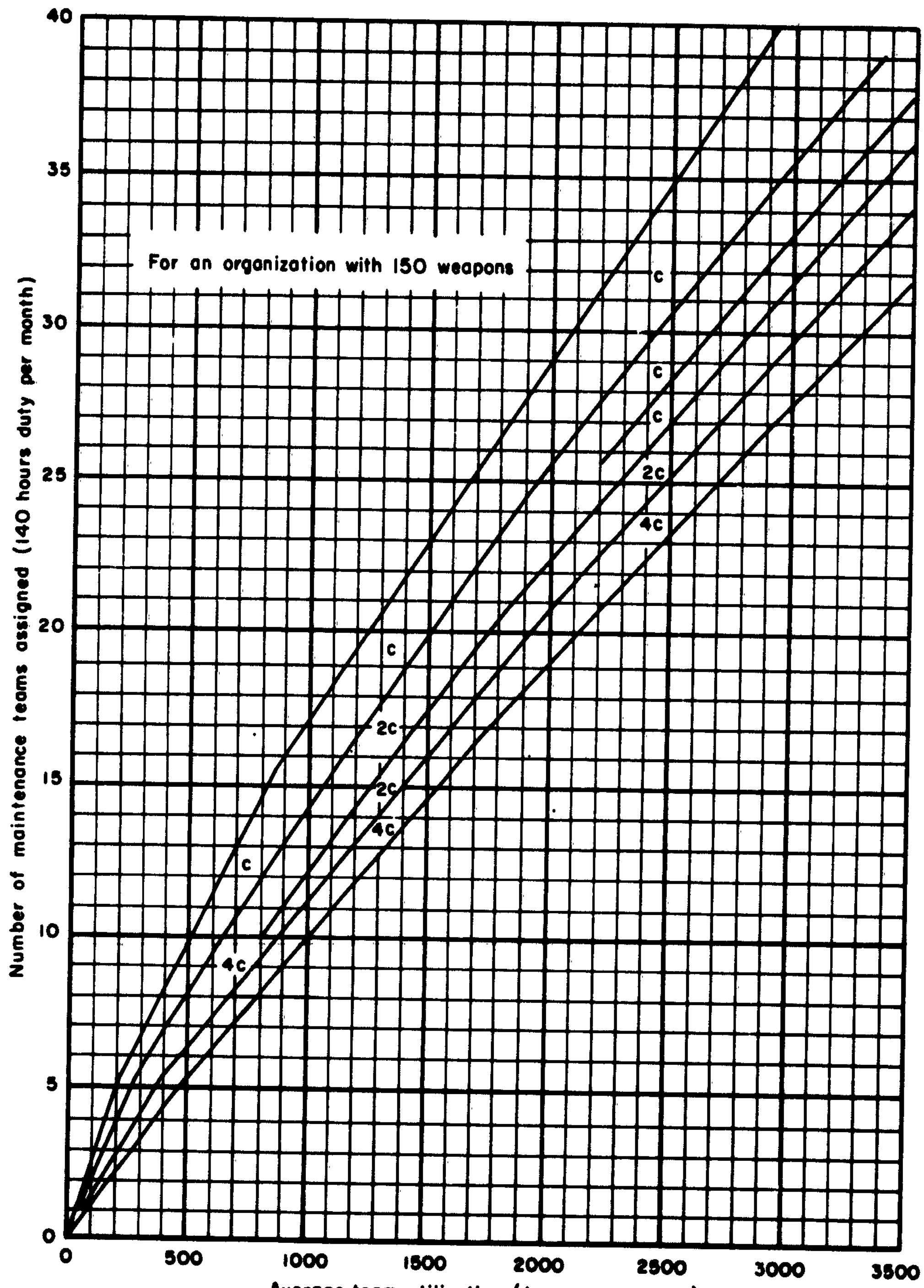

Fig. 6 — Manpower requirements versus monthly utilization

the "rays" as the equipment. If, with 1750 hours utilization per month, only four (4) vans have been procured, we have selected a "ray" that is down about 2.2C from the top. Thus 21 teams are the compatible quantity to provide. To illustrate further, assume there are 7 shifts per week of 12 hours each, 1750 hours of basic utilization including van repair, and that we have decided to buy 8 vans (using utilization of 2 x 1750 = 3500 hours for the equipment). Thus we are down about 0.5C from the upper line. For personnel, we use the 1750 hours utilization, and would procure 24 teams.

In both equipment and manpower requirement determinations we have been considering only those maintenance actions which occurred as a result of random demands, and not those which are specifically scheduled such as inspections, recalibrations, retargeting, etc. We believe that the best way to handle this latter requirement is to compute the monthly utilization for such scheduled maintenance, and buy for it on a nearly 100 per cent utilization basis after accounting for equipment breakdowns and shift policy. Another way would be to make some use of the unutilized time of the vans (and personnel) purchased for unscheduled maintenance, then invoke a policy which would not permit vans to be sent out on scheduled maintenance unless some were remaining for possible unscheduled maintenance. In spite of the policy of holding some vans back, some degradation in operational readiness will result because on occassion more unscheduled demands will arise before other vans have returned. We have not been able to devise a better way of handling this.

IV. THE ASSUMPTIONS, THEIR EFFECTS AND MODIFICATIONS

The analytical tool described in this Memorandum is subject to a number of assumptions, restrictions, and limitations. Some of these arise due to certain natural physical characteristics or limitations. Others have to do basically with the characteristics of human beings, either as specific limitations, or causes of procedural expediency. Still another group is tied to the characteristics of management, or management policies. Thus the first group is subject to relatively little in the way of control; the second somewhat more; and the third is, to a major extent, amenable to the directives of the organization. Hopefully, the sum total of non-reality thus incurred is small by comparison with either the uncertainties of predictive reliability information or of future operational policies. This Section examines each of the assumptions or simplifications necessary for the use of the method described earlier, evaluates the likely effect, and, where possible, details the procedure for reducing any resulting unreality to an acceptably low level. Additionally, as part of the validation of the technique presented in this Memorandum, we compared a variety of situations using a quite sophisticated computer simulation. The numerical results were found to be essentially equivalent except under conditions of extreme, hence uneconomic, queuing.

NATURAL CHARACTERISTICS OR LIMITATIONS

This sub-section is concerned with assumptions whose necessity or expediency are somehow related to what might be called physical reality or the "real world." These assumptions concern phenomena

which fall primarily outside the sphere of human influence, so that while we may sometimes make analytical allowances or empirical corrections for them, their existence remains.

The Form of the Service-Time Distribution

Generally, repair jobs will vary in the time required for a maintenance or repair team to make preparations (be briefed, and gather tools and parts), travel to a remote site, analyze the existing difficulty, make the necessary repairs and/or adjustments, check the effectiveness of their actions, return to their base of operations, and report their findings and actions. The most obvious variables are the distance to the site, the weather, the possibility of improper diagnosis, (resulting, among other things, in not having brought correct tools or parts) and other usually unforeseen or unforeseeable difficulties. It should be evident that repair time is subject to considerable variability. This topic has recently been the subject of substantial research. Studies have shown that repair times for a fair variety of jobs (varying in complexity and equipment type) can usually be characterized best by the logarithmic-normal distribution.[24] Unfortunately, (or seemingly so) the vast majority of research efforts concerning queuing assume a negative exponential distribution of times-to-repair, while some information on point distributions (i.e., no variability) is also available. It has been shown that a parameter called the coefficient of variation is the crucial one in assessing the effect of a particular frequency distribution of times-to-repair in a queuing problem. For the point distribution, this ratio is zero; for the negative exponential,

it is exactly one. Fortunately, these two extreme cases seem to bracket the documented real-life examples to a remarkable degree. Furthermore, experience with an all-computer simulation of the Minuteman* indicates that variabilities introduced by travel distances and end-of-shift delays make the assumption of an exponential distribution quite good, even when the actual work-times are arbitrarily held constant. In the light of these facts, it appears that the assumption of an exponential distribution of service times, as made in the Peck and Hazelwood tables, gives waiting times which are only very slightly too long. In other words, the resulting predictions of the number of economically justifiable crews or equipments will be slightly high. In no case have we found this bias to exceed one unit (crew or equipment). In most instances and particularly for low numbers of units, the exponential assumption gives an identical answer to more comprehensive, ambitious, exact, or exotic solutions.

Off the Air for Other Failures

A fundamental assumption in the Peck and Hazelwood tables (and in this Memorandum) is that failures can only occur while the system is in operation. Thus a system which is inactive, whether waiting for service or having it performed, can generate no failures until it becomes operative again. Historically, this assumption agrees quite closely with observations of failure characteristics of a variety of systems, including mechanical, electro-mechanical, and

*A modification of a complex model developed by The Boeing Company was used.

electronic; it appears to be a valid assumption for the overwhelming majority of the parts of the Minuteman system.

However, the queuing tables take no account of the fact that a subsystem may be inoperable (and thus producing no failures) for reasons other than its own failure. For example, the entire Minuteman system may be shut down when a failure is detected in a particular subsystem, e.g., the re-entry vehicle. Thus failures in each of the other subsystems will be "postponed" at least the length of the shutdown. In a given time interval, there will then be fewer failures of all the other subsystems than there would have been had the defective subsystem alone been shut down. The net effect, in a large number of systems like those in a wing of 150 Minuteman missiles, is that the number of such systems generating failures is nearly always less than 150. It is, in fact, equal to the number of systems on alert, and thus in an operating and failure-generating condition.

A relatively simple expedient can be used to account for the reduction in failures. In using the queuing tables, the population figure for each team (or equipment) type can be chosen to eliminate the number of systems that are inoperative for reasons <u>not</u> related to that type. In other words, the equivalent population for a particular team or equipment can be computed as either (a) the average number of systems on-alert, plus the average number out-of-commission waiting for service from a particular team or equipment, plus the average number that team or equipment is servicing, or (b) the total number of systems (for example, the 150 mentioned previously), less only those either waiting for or being

serviced by teams or equipments other than the one(s) in question. The detailed procedure assumes a population, and then computes the average number waiting and being serviced for each team or equipment type. From these results, a new population is computed for each team or equipment as above, and the process is repeated. For what appear to be economically reasonable waiting times, it is rarely necessary to iterate more than once to achieve a stable solution. The results obtained in this manner appear to be in slightly better agreement with simulation results than those given by using the same (though less than the total) population for all team or equipment computations. Except in cases of considerable (and decidedly uneconomic) queuing, we believe the refinement is not worth the extra effort involved.

Team Interactions

The previous sub-section considered one way in which requirements for different teams or equipments are interrelated. Other interactions will exist if more than one team (or equipment) is required to repair a particular failure. For teams whose work must be performed concurrently (or nearly so), there is ordinarily a small, but finite probability that a failed system will be waiting for not just one, but two (or more) teams or equipments at the same time. (This "overlap" of waiting times is analogous to AOCP when two or more parts are needed.) Because of this, the value (toward alert time) of an additional team or equipment is slightly

overestimated. For economically rational levels of waiting, the effect is negligible, as judged by the results of simulation.*

For teams or equipments whose work must be immediately sequential for a given type of failure, the same problem exists. Furthermore, in this case advance notice, which may permit some scheduling advantages is available to the follow-on groups. Only when the time sequence of activity is arbitrary can teams or equipments be considered independent.

Return Time

The queuing tables take no account of travel time as such. Consequently, we have added travel time both ways to the average on-site work time in order to account for all active team or equipment time, when they are unavailable for other jobs. Although the tables now consider the system out-of-service during all such active time, it is not ordinarily necessary to make a correction for return trip time (when the missile is once again on alert). Since the tradeoff is between resource costs and waiting time (not working time), this factor is of no consequence unless one is also trying to compute a predicted alert level at the same time (a purpose for which this study is not intended).

Daylight Hours

If a particularly large piece of equipment can only be moved over the road during daylight hours, this must be reflected in the

*If the waiting for different teams was independent, the effect (the product of two or more small probabilities) would clearly be of second order importance. Because of the obvious interrelationship, it is not necessarily so.

expected average service time required by such equipment for each service demand. One way to handle this situation is to assume that the departure of such an equipment from the maintenance facility or the site should be made only at dawn. Thus, if the maximum distance is 150 miles and the average speed is 20 mph, the trip takes at most $7\frac{1}{2}$ hours, which is within the year-round daylight span of any point in the continental United States (8 hours minimum at 49° latitude). If average speed is lower or maximum distance higher, there may be cases during winter when some trips will require an overnight stop en route. For the dawn departure, each applicable failure during the previous 24 hours will be delayed until that time, for an average delay of 12 hours, which should be added to anticipated work and travel times. The same is true (usually) of the return trip. This assumption is a slightly pessimistic one, since nearby sites can be reached during daylight with a departure substantially after dawn. Then too, trips to more distant sites could be started considerably after dawn, and an overnight stop could be made at any convenient LCC en route, so that the average delay in the departure of a slow-moving vehicle would be quite small.

Late in Shift Delay (Administrative)

There may be reasons other than a daylight requirement for making many, or even most dispatches from the maintenance facility at the start of a work shift. Considering the substantial amount of travel time required to reach many of the missile sites, teams dispatched late in a shift may not have time for any useful work after arrival on-site and before the end of an 8- or 12-hour shift.

(On the other hand, it is reasonable to ask once again why they should not then proceed directly to the appropriate launch control center for the off-shift hours, so they can begin work very close to the start of their next shift).

If such a policy exists, in whole or in part, the effect is to add an administrative lag time to work and travel times in order to arrive at an estimate of missile downtime when a failure occurs. For a 21-shift policy, this maximum lag will be about $\frac{1}{2}$ shift on the average, or 4 hours. At the other extreme (5 daytime shifts a week) the average delay, considering weekends, is approximately 22 hours each time a failure occurs. The latter figure creates a serious question regarding the advisability of a 5-shift-a-week policy in combination with start-of-shift dispatching of maintenance resources.

Ground Transportation, Weather, Etc.

In the development and application of the method for determining economically desirable support levels, we have assumed that the mode of transportation would be motor vehicles over a road network. We further assumed that Air Force surveillance and maintenance of the network would counter the effects of weather so that it could be ignored (except for the daylight problem mentioned previously). We have not explicitly considered the effect of support by air for either unexpectedly necessary parts or diagnostic teams. But if a multiple-shift operation is used, that portion of crew time spent in ground travel makes it almost imperative to evaluate the possibilities of transporting relief crews by air. For a single shift, it

is not clear how air support could improve the situation, since most crews are associated with ground vehicles and other heavy equipment. However, it may be interesting to consider the limited application of large helicopters to this problem.

HUMAN CHARACTERISTICS

This sub-section covers assumptions related primarily to what we think of as human characteristics or limitations.

Errors of Diagnosis or Dispatch

The procedures described in earlier sections for establishing average work times did not include allowances for errors of one kind or another. Examples of errors which might increase either the frequency of repair demands or their length (for a net increase in total work and travel) are, (1) ambiguous indication of the likely fault by the VRSA* system, (2) on-site errors in diagnosis or procedure, (3) errors regarding travel routes, and (4) incorrect parts or equipment. In each of these cases, a probabilistic allowance can be added to projected work times or service demand frequency. After some experience is gained in the operation of a missile organization, these considerations will become a part of the empirical frequency and time data, and need not be considered separately.

Travel for Off-Shift

It should be evident from some of the previous sub-sections that we expect many jobs to be incomplete at the end of a shift.

*Voice Reporting Signal Assembly.

The anticipated procedure for these cases is to have the crew proceed by road vehicle to the nearest launch control center and spend the off-shift hours there, returning to the site at the start of their next shift. We have assumed that crews were on site at the start and finish of the shift. If they are not, an allowance for travel time to and from the Launch Control Center must be added to the average work and travel time for each full-shift period.

<u>Monthly Limit on Working Hours</u>

The procedure of providing economically desirable numbers of people and equipment to cope with variabilities in the demand for service results in a considerable amount of idle time among crews and equipment. This happens because one of the fundamental assumptions in the queuing computations is that each servicing unit (crew, equipment, or combination) is on call whether it is being used or not. In some cases during slack periods, a commander may be able to schedule some time off for one crew (among several) that would otherwise be on duty. Likewise, overtime (compensated by time off at a later quiet period) could be used to a degree during peak loads. In both instances, the workload picture can change so rapidly that these expediencies may be of extremely limited usefulness. For this reason, and the realities of military duties, we have assumed that personnel may average only 140 hours of assigned time per month, including work on-site, travel, and idle time while on duty at the support center.

MANAGEMENT CHARACTERISTICS

The following items are consequences of the management system. In each case, improvements are possible, and perhaps desirable, but the assumptions are intended to reflect current plans for management policies.

FIFO and Potential Improvements

The Peck and Hazelwood tables are based on a first-in-first-out policy (FIFO) with jobs processed in their order of arrival. When service times vary, as with differing travel distance and job lengths, it is well known that a somewhat different policy, namely shortest job first, results in somewhat better performance under queuing conditions. In general the FIFO assumption in the tables is compatible with current plans.

Non-Critical Jobs

We have assumed that certain repair jobs to which the RPIE (real property installed equipment) repair teams respond may be non-critical. These are the jobs whose failure does not affect the missile's alert status. For teams responding to such jobs, the suggested procedure for arriving at economically justified numbers is to segregate the non-critical jobs and provide enough support (teams and equipment) to accomplish the required workload on the basis of nearly 100 per cent utilization (i.e., almost no allowance for variability in arrival times or service times). Then a support requirement calculation is made for the critical jobs according to the methods described earlier. When these two groups are pooled, the beneficial effect of the pooling relative to queuing

seems to balance the shortcomings of providing the non-critical workload support on the basis of nearly 100 per cent utilization. This conclusion is made on the basis of simulation runs where a rule was in effect that if only one team or equipment was available, (all others being occupied) it would not be sent on a non-critical job. This rule should consider the total number of such teams and hold back a percentage.

TOC and Scheduled Maintenance

Anticipated workloads due to Technical Order Compliance (TOC) and scheduled maintenance of one kind or another (example: periodic retargeting) can be handled in essentially the same fashion as the non-critical jobs just described, provided their occurrence and duration have the same "spread-out" quality over time. If the jobs occur essentially all at once, it will probably be necessary to provide, at appropriate times, special teams other than those normally assigned to the wing organization. Another alternative, not evaluated because of the lack of a specific example, is to strike a compromise between the appropriate long-term support level for unscheduled maintenance, and a level which could accomplish anticipated TOC or scheduled maintenance in an acceptable period of time if unscheduled work were temporarily ignored. The implications are a temporary decrease in alert levels, and a subsequent recovery period, neither of which may be acceptable for a first-line weapon system.

V. CONCLUSIONS

Manpower and equipment requirements are presently established by assuming that work will arrive in a uniform fashion. The unrealistic nature of this assumption was reiterated as recently as the July 1962 Minuteman QPRI. Random failures and variable repair times are more typical of actual experience.

This more realistic problem can be treated by finite queuing theory. Peck and Hazelwood have computed and tabulated a spectrum of solutions to this problem for a broad range of values of such quantities as the number of items in the inventory, the expected number of failures, the time to make a repair, and the number of repair teams.

In addition to the randomness of the failure and repair patterns, the work shift policy and cost considerations are important aspects of the problem.

The basic information needed to select appropriate quantities of equipment and personnel is in essence the same as that required for MIL-D-9412C (used in current QPRI documents), with the addition of some simple cost information.

Using curves derived from the Peck and Hazelwood tables, we can weigh the value (in greater force capability) of one additional unit of resources against the cost of that unit, and thus strike a cost-effectiveness balance which tends to give the maximum capability for a given total cost, or minimizes the cost to achieve a given capability. In addition to arriving at a desired quantity, we can evaluate the penalty (in terms of reduced capability) for not providing

that quantity, or alternatively, of not meeting projected reliability, maintainability, or cost goals.

We believe use of this technique will provide better numerical estimates of manpower and equipment requirements than methods currently being used.

Appendix A

CONSTRUCTION OF THE CURVES

This Section will demonstrate, by means of a simple but pertinent example, how the curves of Sec. III were constructed with the aid of the Peck and Hazelwood Tables.[23] The specific example is the top curve of Fig. 5, which relates expected equipment utilization per month to the number of equipments required in order to have a minimum (0.05 of 1 per cent or 1 part in 2000) of time lost to queuing. In other words, we are developing the locus of points where the efficiency factor denoted F in the tables has a value of 0.99950.

To do this, we need some information in addition to that already presented. The values of the efficiency factor F in the tables have been rounded to the nearest thousandth. For the specific example chosen, it is also pertinent that when this rounded value is 1.0 (i.e., $F > 0.99950$), no entry appears in the table for that combination of the service factor X and the number of servers M. Finally we need to relate the service factor to the expected number of hours of equipment utilization per month. This relationship can be shown to be:

$$\begin{aligned} \text{hours per month} &= 150 \times 730 \times X \\ &= 109{,}500 \times X \end{aligned}$$

if a month is considered to be 730 hours and we have 150 missiles.

Now we search the tables (for $N = 150$) for those values of X where each value of M first appears (usually with $F = 0.999$), and note the previous value of X where the same value of M is omitted, thus:

X	M	F	Hours/Month
.004	(no entry)		438
.005	2	.999	548
.007	(no entry)		767
.008	3	.999	876
.011	(no entry)		1205
.012	4	.999	1314
.015	(no entry)		1643
.016	5	.999	1752
.019	(no entry)		2081
.020	6	.999	2190
.023	(no entry)		2519
.024	7	.999	2628
.028	(no entry)		3076
.030	8	.999	3285
.032	(no entry)		3504
.034	9	.999	3723
.036	(no entry)		3942
.038	10	.999	4161
.042	(no entry)		4599
.044	11	.999	4818
	etc.		

When plotted, these pairs of observations define the narrow region through which the F = 0.9950 curve must pass, as shown in Fig. 7. The derivation of the other curves in Figs. 5 and 6 is similar.

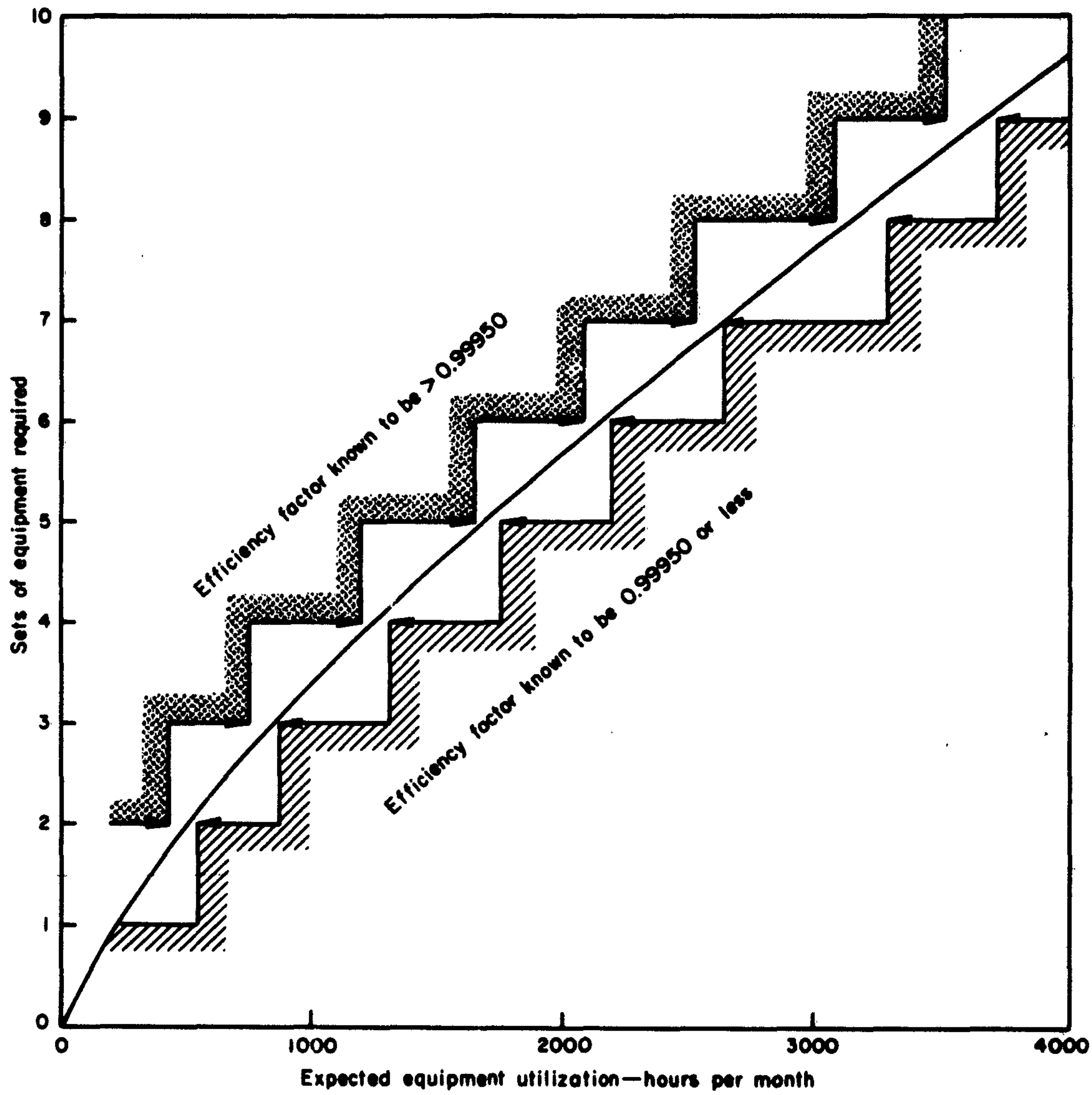

Fig. 7—Equipments required versus monthly utilization for an "efficiency factor" of 0.99950

Appendix B

AN ALTERNATE METHOD OF COMPUTING ECONOMICAL QUANTITIES OF MAINTENANCE MANPOWER AND EQUIPMENT

This Appendix contains the information necessary for determining economical quantities of support resources according to a method first suggested by Mangelsdorf[25] at M.I.T., and more recently used at Boeing.[26] Figure 8 shows the economically justifiable procurement quantity of a given resource according to its anticipated use and cost characteristics. One enters the diagram on the horizontal axis with the expected number of hours of use per month (expected failures per month x number of hours required to repair a failure), and on the vertical axis with the ratio of

$$\frac{\text{the cost of one unit of resource}}{\text{the cost of a one missile "slice" of the wing}} .$$

The intersection defines the desirable quantity, which was determined on a cost-effectiveness basis.

The only real advantage of this method is its utter simplicity, and consequent attraction as a tool for routine use. Its disadvantages are:

1) The alert time lost to waiting is not available, so that

2) the tradeoff values are not available.

3) An infinite population is assumed; for a population of 150 missiles, the error is about 2 per cent (negligible). For smaller groupings (i.e., 25 aircraft at a base) the infinite population assumption will lead to severe inaccuracies; a correct diagram can be generated for any particular population, but will only be good for that population.

4) It does not permit appropriate allocation from a fixed budget to equate the marginal utility of the resources to be purchased.

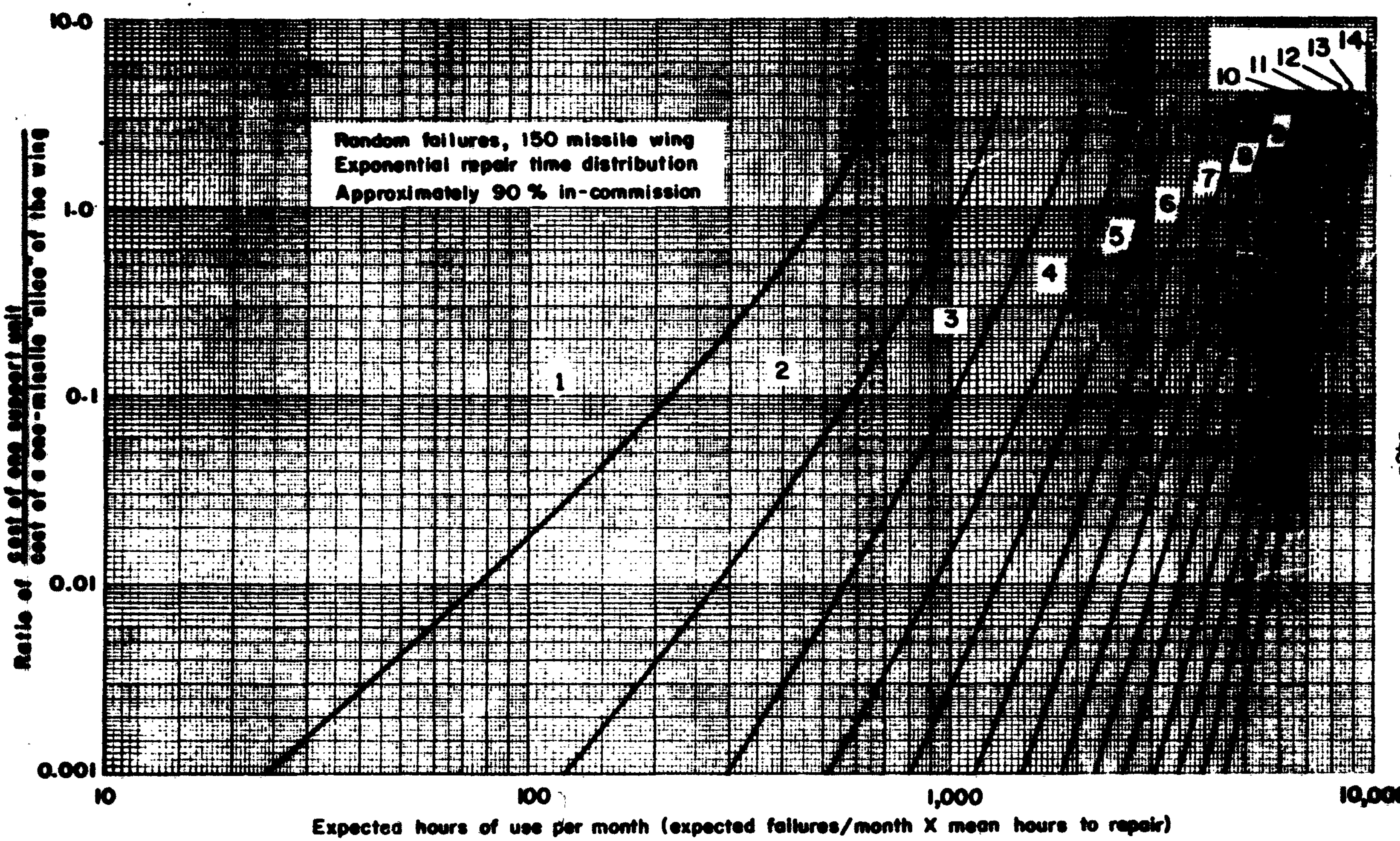

Fig. 8--Decision map for economical quantities of maintenance resources

REFERENCES

1. WDT Exhibit 57-7, Maintenance Analysis Program for Ballistic Missile Weapon Systems, October 1957.

2. Military Specification MIL-D-26239 (USAF), Data, Personnel Information for Weapon Systems, 19 November 1957.

3. AFBM Exhibit 58-18C, Qualitative Personnel Requirements Information.

4. Military Specification MIL-D-9412 C, Data for Ground Support of Weapon Systems, Subsystems and Equipment.

5. Voosen, B. J., E. Zabel, and D. S. Stoller, Firing Capabilities Versus Firing Objectives for the Atlas ICBM (U), The RAND Corporation, RM-1920, August 26, 1957 (Secret).

6. Sewell, W. P., Maintenance-Operations Interactions at Base Level, The RAND Corporation, RM-1960 (AD 133045), August 1, 1957.

7. Levine, R. A., and R. B. Rainey, A SAC Alert Concept for the Immediate Future (U), The RAND Corporation, RM-2303, January 5, 1959 (Secret).

8. Levine, R. A. and R. B. Rainey, The Base Maintenance-Operations Model used in RAND Logistics Research, The RAND Corporation, RM-2374 (AD 220605), May 4, 1959.

9. Levine, R. A., and R. B. Rainey, Maintenance-Operations Interactions (U), The RAND Corporation, RM-2437, August 18, 1959 (Secret).

10. Voosen, B. J. and D. D. Corona, Misslogs: A Game of Missile Logistics, The RAND Corporation, RM-2455 (AD 232507), September 28, 1959.

11. Bell, C. F., ICBM Operational and Support Concepts for the Mid-60's: An Argument for Large Storable Propellant Missiles and Other Things (U), The RAND Corporation, B-133, August 7, 1959 (Secret -- Restricted Data).

12. Bell, C. F., An Evaluation of Logistics Aspects for the Minuteman Program (U), The RAND Corporation, B-259, May 24, 1961 (Secret).

13. Voosen, B. J., A Method for Estimating Direct Squadron Personnel Requirements via Malfunction Rates: An Application to the Titan ICBM (U), The RAND Corporation, RM-2009-1, April 4, 1958 (Confidential).

14. W. Haythorn and E. Pickrel, Estimating Personnel and Equipment Requirements, The RAND Corporation, B-129, July 1, 1959.

15. Rauner, R. M. and W. A. Steger, Simulation of ICBM Support (U) The RAND Corporation, R-369 (AD 323749), November 1, 1960 (Secret).

16. Bean, E. E. and W. A. Steger, The Malfunction-Generation Model Used in the RAND Logistics Laboratory Simulation of an ICBM Squadron (U), The RAND Corporation, RM-2442 (AD 320615), September 1, 1960 (Secret).

17. Ballistic Systems Division, D2-5859, Vol. I, Qualitative Personnel Requirements Information for WS-133A Minuteman Hardened and Dispersed (U), July 1962 (Secret).

18. Ballistic Systems Division, D2-6951, Vol. II B, Maintenance Ground Equipment Failure Rate Data (U), revised April 1962 (Secret).

19. Ballistic Systems Division, BSQ-169-1, Minuteman Operational Support Planning Failure Rates (U), 15 May 1962 (Secret).

20. Knowles, H. E. MTBF Apportionments for Production Equipment (U) Autonetics, EM-7667-2, May 21, 1962 (Secret).

21. The RAND Corporation, A Million Random Digits with 100,000 Normal Deviates, The Free Press, Glencoe, Illinois, 1955.

22. Molina, E. C., Poisson's Exponential Binomial Limit, D. Van Nostrand Co., Inc., New York, 1957.

23. Peck, L. G. and R. N. Hazelwood, Finite Queuing Tables, John Wiley and Sons, Inc., New York, 1958.

24. Bovaird, R. L. and H. I. Zagor, Downtime Distribution for Complex Electronic Systems, Tempo Report RM59TMP-59, December 15, 1959.

25. Mangelsdorf, T. A.,Application of Waiting Line Theory to Manufacturing Problems, Interim Technical Report No. 5, M.I.T. Project on Fundamental Investigations in Methods of Operations Research (adapted from a thesis submitted to The School of Industrial Management, May 16, 1955).

26. Ballistic Systems Division, BSD TR-62-1, Vol. III, Minuteman WS-133A Category II Test Program Plan, Operations, Maintenance, and Logistics Evaluation and Analysis (U), prepared by The Boeing Company, July 15, 1962 (Secret)